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ANABRANCHING RIVERS: THEIR CAUSE, CHARACTER AND CLASSIFICATION

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ABSTRACT

Anabranching rivers consist of multiple channels separated by vegetated semi-permanent alluvial islands excised from existing floodplain or formed by within-channel or deltaic accretion. These rivers occupy a wide range of environments from low to high energy, however, their existence has never been adequately explained. They occur concurrently with other types of channel pattern, although specific requirements include a flood-dominated flow regime and banks that are resistant to erosion, with some systems characterized by mechanisms to block or constrict channels, thereby triggering avulsion. The fundamental advantage of an anabranching river is that, by constructing a semi-permanent system of multiple channels, it can concentrate stream flow and maximize bed-sediment transport (work per unit area of the bed) under conditions where there is little or no opportunity to increase gradient. On the basis of stream energy, sediment size and morphological characteristics, six types of anabranching river are recognized; types 1–3 are lower energy and types 4–6 are higher energy systems. Type 1 are cohesive sediment rivers (commonly termed anastomosing) with low w/d ratio channels that exhibit little or no lateral migration. They are divisible into three subtypes based on vegetative and sedimentary environment. Type 2 are sand-dominated, island-forming rivers, and type 3 are mixed-load laterally active meandering rivers. Type 4 are sand-dominated, ridge-forming rivers characterized by long, parallel, channel-dividing ridges. Type 5 are gravel-dominated, laterally active systems that interface between meandering and braiding in mountainous regions. Type 6 are gravel-dominated, stable systems that occur as non-migrating channels in small, relatively steep basins. Anabranching rivers represent a relatively uncommon but widespread and distinctive group that, because of particular sedimentary, energy-gradient and other hydraulic conditions, operate most effectively as a system of multiple channels separated by vegetated floodplain islands or alluvial ridges.

KEY WORDS anabranching rivers; anastomosing rivers; river pattern; river classification; channel avulsion; alluvial islands; alluvial ridges

INTRODUCTION

Schumm (1985) recognized that river patterns provide information on a river's physical characteristics and behaviour; they reveal something of the dynamics of a river system. Gregory (1985) stated that classification is necessary for the consistent description of river channels in different environments and for the better understanding of river genesis and processes. The objectives of this paper are: firstly, to examine and describe the range of conditions in which anabranching systems form; secondly, to group this wide variety of anabranching systems into different types; and finally to explain why, in a wide range of environmental settings, some rivers form anabranches.

Alluvial channels respond to changes in regional physiography, hydrology and sediment load by adjusting their hydraulic geometry and river pattern. Their geometry can vary from narrow and deep to wide and shallow on a continuous scale, but pattern is more complex, necessitating subdivision into several classes that can be, but are not necessarily, part of a continuum. In a revision of Leopold and Wolman's (1957)

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classification, anastomosed channels are now recognized as a pattern very different from braided (Schumm, 1968; Rust, 1978; Knighton and Nanson, 1993), with which they had earlier been associated, and are one of a number of anabranching systems defined below. While the causes of meandering and braiding have been thoroughly investigated and are at least partially understood, the cause of river anastomosis is largely unknown. Yet anastomosing rivers are widespread, having been described in western Canada (Smith, 1973, 1983; Smith and Smith, 1980; Smith and Putnam, 1980; King and Martini, 1984; Smith *et al.*, 1989), South America (Baker, 1978; Smith 1986), the United States (Schumann, 1989; Miller, 1991), Australia (Schumm, 1968; Riley, 1973; Riley and Taylor, 1978; Rust, 1981; Rust and Nanson, 1986; Nanson *et al.*, 1986, 1988) and Ireland (Harwood and Brown, 1993).

In a recent paper, Knighton and Nanson (1993) examined anastomosing rivers within a proposed continuum of channel pattern that is based on flow strength, bank erodibility and sediment supply, an analysis into which the selected low-energy anabranching systems fit reasonably well. However, in undertaking that analysis, it became clear that, while the term 'anastomosing' has been largely restricted to fine-grained, low-energy rivers (e.g. Smith, 1973, 1983; Smith and Smith, 1980; Smith and Putnam, 1980; Carson, 1984), the full extent of channel systems that anabranch is much broader. Indeed, in a review of fluvial facies models, Hickin (1993) recently suggested that the anastomosing model is a premature concept based on the study of relatively few rivers, the full development of which should await detailed investigation of a much wider range of types. Consequently, there tends to be a confusing nomenclature for multiple channel systems. While the separate use and meaning of the terms braiding and anastomosing are now well accepted (Schumm, 1968; Smith, 1973; Riley, 1975; Rust, 1978; Smith and Smith, 1980; Smith and Putnam, 1980), the requirement that the latter are necessarily high-sinuosity streams (Rust, 1978) does not hold. Mollard (1973) uses anastomosing to define high-energy, multiple-channel, low-sinuosity streams in a category similar to that defined by Neill (1973) and Church (1983) as wandering gravel-bed rivers. Brice (1984) and Schumm (1985) adopt the term 'anabranching' to describe multichannel systems in diverse settings, within which individual channels may meander, braid or be relatively straight, and it is used here in the same sense.

It would seem that all planforms, including anabranching, are responses to complex sets of interacting variables. Meandering is common to all other patterns, even if it is sometimes in the form of a meandering thalweg in an otherwise straight channel (Schumm and Khan, 1972) or in the sinuous individual channels of a braided system. Braiding on a large scale is more restricted in its distribution, but its definition, based as it is on the exposure of mid-channel bars, is very much stage-dependent; a tendency for braiding at low to moderate flow is common in a wide range of rivers not normally described as braided. Anabranching systems occur in virtually all environmental settings, from alpine gravel-bed streams to lowland muddy and organic deltas, and they can be classified into a variety of types.

DEFINITIONS AND EXCLUSIONS

As noted by Smith and Putnam (1980), the term anastomosis was initially used in fluvial geomorphology by Jackson (1834, p. 79) and later by Peale (1879) to describe multiple-channel systems separated by alluvial islands in the upper Green River, Wyoming. It is now well accepted that braiding consists of flow separating around exposed bars within the channel. As distinct from braiding, Brice (1984) and Schumm (1985) describe anabranching as occurring where a river is divided by islands. It is proposed here that an *anabranching river* be defined as *a system of multiple channels characterized by vegetated or otherwise stable alluvial islands that divide flows at discharges up to nearly bankfull.* These islands may be excised by channel avulsion from extant floodplain, developed from within-channel deposition or formed by prograding distributary channels within splays or deltas. Common usage (e.g. Smith and Smith, 1980; Smith and Putnam, 1980) requires that the term 'anastomosing' be limited here to a specific subset of relatively distinctive low-energy anabranching systems associated with mostly fine-grained or organic deposition, a limitation also applied to the term by Carson (1984) and Knighton and Nanson (1993). In any anabranching, as opposed to braiding, system, the islands usually persist for decades or centuries, support well-established vegetation and have relatively stable banks. They are at approximately the same elevation as the floodplain, and the channels between the islands can be braided, meandering or straight.

As distinct from channel migration, the term 'channel avulsion' is used here to indicate the relatively sudden and major shift in the position of a channel to a new part of the floodplain (first-order avulsion), or the sudden reoccupation of an old channel on the floodplain (second-order avulsion). It does not relate here to the relatively minor switching of channels within a braid train (e.g. Leddy *et al.*, 1993) (third-order avulsion).

Because of the association with low-energy, fine-grained systems, Carson (1984) avoided the use of the term 'anastomosing' for describing coarse-load, high-energy rivers that are clearly multichannelled. Church (1983), Desloges and Church (1987, 1989) and Brierley and Hickin (1991) illustrate an often confusing pattern of braiding and meandering channels in the category of wandering gravel-bed rivers (Church, 1983). These are commonly anabranching channels separated by semi-permanent and well-vegetated islands.

Only anabranching channels which share a common alluvial floodplain essentially contemporaneous with present hydroclimatic conditions (Nanson and Croke, 1992) are considered here. Excluded are multichannel distributary systems with channels that divide but do not rejoin, and those with islands separated by bedrock or extensive areas of ancient alluvium. Unfortunately, the Indogangetic systems are too diverse and complex to be averaged, and while individual reaches warrant separate comparative studies, the published literature is insufficiently detailed to permit their inclusion (e.g. Coleman, 1969; Bristow, 1987, 1993; Klassen and Vermeer, 1988; Richards *et al.*, 1993; Singh *et al.*, 1993; Wells and Dorr, 1987).

ANABRANCHING STYLES

Leopold and Wolman (1957) proposed a fundamentally important tripartite system of straight, meandering and braiding channels, but these patterns are not mutually exclusive and several intermediate styles exist that cannot easily be categorized. Knighton and Nanson (1993) describe anastomosing (low-energy, multiple-channel) rivers as part of a continuum of channel pattern defined in terms of a three-dimensional space where the axes are flow strength, bank erodibility and local sediment budget. Anastomosing is represented by low flow strength, resistant banks and a sediment supply which (slightly) exceeds that removed by onward transport. However, as will be illustrated here, the broader category of anabranching, with its variety of types, does not fit this relatively neat scheme.

Hydraulic, physiographic, geological and botanical conditions each appear to play a role in causing a variety of anabranching river types. This study is preliminary and recognizes six main types arranged roughly in order of increasing specific stream power ($\gamma QS/w$, where γ is the specific weight of water, R the hydraulic radius, Q the flow discharge, S the slope and w the channel width), but also divided on the basis of sediment texture and river morphology. Their distribution on a slope–discharge plot is presented in Figure 1, while their specific features are described in Table I and selectively summarized by types in Figure 2.

Lane (1957), Leopold and Wolman (1957), Chang (1979a,b) and Ferguson (1987) have used bivariate plots of channel slope and bankfull discharge to differentiate river types on what is effectively a continuous scale of stream power at approximately bankfull flow, with power related to sediment size and transportability. While a useful first approximation of channel types can be achieved, a simple bivariate relationship cannot encapsulate the complexity of channel processes. Further differentiation requires the inclusion of morphological (channel and planform) characteristics that are often dependent on variables, such as vegetation, that are difficult to quantify (Hickin, 1984). The classification proposed here initially differentiates on the basis of stream power (Figure 1) but additional categorization of stream type is based on the fluvial morphology, sedimentology and processes (Table I and Figure 2).

Type 1: Cohesive sediment anabranching rivers (anastomosing rivers)

These are the classic anastomosing rivers of relatively uniform and narrow width, with low gradients and stable cohesive banks (Smith and Smith, 1980; Rust, 1981). They are often, but not always, sinuous, exhibit almost no lateral migration and relocate by avulsion. Stream power is characteristically very low (Figure 1), usually $\leqslant 8\ \mathrm{W\,m^{-2}}$, and channels are frequently canal-like in cross-section. They are divided into three subtypes on the basis of environment and associated sediment type.

Table I. Characteristics of anabranching rivers. These data are obtained from published papers, personal communications and our own sources. Slope estimates include map slopes and field surveys; discharge data are from direct measurements and indirect estimations; channel widths and sinuosities are from field, map and air photograph measurements; sediment texture is from detailed size analysis and qualitative field inspection; and estimates of vertical and lateral activity were obtained from a variety of direct and indirect methods. Specific stream power is a derivative expression based on several estimated values and is presented here estimated to the nearest 5 W

Classification		Geography				Flow characteristics		
Type	Sub-type	River	Reference	Climate	Physiographic setting	Flow regime	Discharge ($m^3 s^{-1}$)	Specific stream power ($W m^{-2}$)
1 Cohesive sediment (anastomosing)	(a) Hyper-humid, organic	Okavango R. fan-plain (middle fan)	McCarthy *et al.* (1988, 1991, 1992)	Highland subtropical	Low gradient fan-plain	Tropical highly seasonal	Q_b 25–50	2–5
	(b) Humid, organo-clastic	Upper Columbia R., B.C., Canada	Smith (1983)	Cold temperate	Intermontane valley	Snowmelt and glacier runoff dominant	Q_b 275	$\leqslant 10$
		Lower Saskatchewan R., Sask., Canada	Smith (1983); Smith *et al.* (1989)	Subhumid cold continental	Lacustrine plain, wetlands	Snowmelt runoff dominant	$Q \sim 500$ Q_b 1400	$\leqslant 10$
		Alexandra R., Alb., Canada	Smith and Smith (1980)	Cold temperate	Intermontane valley	Snowmelt and glacier runoff dominant	Q_b 66	$\leqslant 10$
		North Saskatchewan R., above Rampart Ck, Alb., Canada	Smith and Smith (1980)	Cold temperate	Intermontane valley	Snowmelt and glacier runoff dominant	Q_b 165	$\leqslant 10$
		Mistaya R., Alb., Canada	Smith and Smith (1980)	Cold temperate	Intermontane valley	Snowmelt and glacier runoff dominant	Q_b 34	$\leqslant 10$
		Lower Attawapiskat R., Ont., Canada	King and Martini (1984)	Humid subarctic	Hudson Bay Lowland. Partly estuarine	Snowmelt runoff dominant	Q 508 Q_{max} 3115	
		Magdalena R., Colombia	Smith (1983/1986)	Tropical savanna	Intermontane and foreland basins	Two high-flow periods	$Q_b \sim 8800$	$\leqslant 10$
	(c) Semi-arid, mud-dominated	Cooper Creek, Australia	Rust (1981); Rust & Legun (1983); Rust and Nanson (1986); Nanson *et al.* (1986/1988); Rust and Nanson (1989); This study	Semi-arid	Alluvial plain in shallow syncline	Monsoonal, long duration floods	$Q \sim 40$–100 $Q_2 \sim 150$–1100 Q_{max} 5800–25 000	2–5
		Red Creek, Wy., USA	Schumann (1989)	Semi-arid	Intermontane basin	Snowmelt runoff dominant	$Q_b \sim 13$	~ 10

Sediment characteristics			Channel-floodplain characteristics					
Sediment load	Bed material	Bank material	Sinuosity	Gradient ($m\,m^{-1}$)	w/d	Levees	Vertical activity ($mm\ yar^{-1}$)	Lateral activity
Bedload $\geqslant 50\%$	Fine sand	Plant material	1·2–1·9 1·5 (mean)	0·00035	4 (mean)	Subdued	Channels 50 (max) floodplain nil	Stable
Mixed; 25% as bedload	Coarse sand, granules	Fine sand, silts	Low : 1·16	0·000096	–	Prominent – up to 50 m wide, 2:5 m high	Rising base-level downstream (fan) 6	Narrow point bars but very slow lateral accretion
–	Medium sand	Silts, fine sands	Medium : 1·4	0·00012	$\geqslant 10$	Prominent – up to 1 km wide, 4 m high	Rising base-level downstream (Isostasy) 15	Stable banks; 1873 avulsion
–	Gravel, coarse sand	Mostly silts	Variable : up to 2·5	0·0006	13 (mean)	Prominent – up to 2 m high	Rising base-level downstream (fan) 18	Stable banks; crevassing common
Gravel dominated	Gravel, coarse sand	Mostly silts	Variable	0·0010	16 (mean)	Prominent	Rising base-level downstream (fan) 18	Stable banks; crevassing common
–	Gravel, sand	Mostly silts	Variable	–	15 (mean)	Prominent	Rising base-level downstream (fan) 6	Stable banks; crevassing common
Solution and suspension dominant $14\,mg\,l^{-1}$	Silts and sands	Silty clay	Moderate: $\leqslant 1{\cdot}5$	0·00052	30–140	–	Isotatic rebound at ~ 7 entrenching	Stable; no within-channel bars
10% as bedload	Medium sand $D_{50} \sim 0{\cdot}35$-mm	Mud, fine sand	–	0·000095	–	Prominent – up to 4 km wide	Basin subsidence 3·8	Crevassing and avulsion common
Mixed load (mud moved as sand-sized bedload aggregates)	Muds, sands	Mud, mostly clay	Varible : up to 1·8	0·0002	~ 10 (mean)	Discontinu-ous and sub-dued	0·1 (max)	Stable
Suspended load dominated	$D_{50} = 0{\cdot}003$ mm	86% silt-clay	Moderate: 1·1–1·9	0·0011 (mean)	8–30	Discontin-uous, subdued	–	Stable; periodic avulsion

Table 1

Type	Sub-type	River	Reference	Climate	Physio-graphic setting	Flow regime	Discharge ($m^3 s^{-1}$)	Specific stream power ($W m^{-2}$)
2 Sand-dominated, island-forming		Magela Creek, Australia	Roberts (1991)	Tropical monsoon	Very shallow valley in low-gradient plain	Monsoonal	$Q_b \sim 40$ Q_2 450 Q_{max} 3000–4000	5 5 10
3 Mixed load, laterally active		Thompson R., Vic., Australia	Brizga and Finlayson (1990; pers. comm. 1993)	Humid temperate	Terraced floodplain	Mountainous headwaters minor snow melt	Q_b old channel 90; new channel 280	5–10 45
		Solimoes R. Brazil	Baker (1978)	Humid tropical	Amazon basin	Andean headwaters	–	–
		Murray R., Australia	W. Erskine (pers comm. 1993); J. Urquhart (unpublished, 1973)	Subhumid warm temperate	Wide lowland floodplain	Mountainous headwaters substantial snowmelt	$Q_2 \sim 650$	2–25
4 Sand-dominated, ridge-forming		Durack R., Western Australia	Wende (in prep.)	Tropical monsoon	Bedrock plateau	Monsoonal	$Q_2 \sim 1600$	10–35
		Sandover R., N.T., Australia	Tooth (in prep.)	Tropical semi-arid	Lowland floodout	Desert episodic	$Q_b \sim 900$	
		Woodforde R., N.T., Australia	Tooth (in prep.)	Tropical semi-arid	Lowland floodout	Desert episodic	Q_b 400	20–40
5 Gravel-dominated, laterally active		Bella Coola R., B.C., Canada	Church (1983); Desloges and Church (1987, 1989)	Cold temperate	Intermontane valley	Snowmelt runoff dominant	$Q_{2\cdot3}$ 350	65
		Athabasca R., at Whitecourt, Alta,Canada	Kellerhals *et al.* (1972)	Cold continental	Confined in incised valley on forested plain	Snowmelt and glacier runoff dominant	Q_2 1300	45
		Nth Saskatchewan R. at Rocky Mt. House, Alta, Canada	Kellerhals *et al.* (1972)	Cold continental	Intermontane valley	Snowmelt and glacier runoff dominant	Q_2 700	115
		Oldman R. at Lethbridge, Alta, Canada	Kellerhals *et al.* (1972)	Subhumid continental	Confined in incised valley on a plain	Snowmelt and glacier runoff dominated	Q_2 570	45
		Squamish R., B.C., Canada	Brierley and Hickin (1991, 1992)	Cold temperate	Confined in mountain valley	Snowmelt and glacier runoff dominated	$Q_{2\cdot3}$ 1200	($w = \sim 200$ m) 80–100
		Gloma R., Norway	Nordseth (1973a and b)	Cold temperate	Confined in mountain valley	Snowmelt dominated	$Q_{2\cdot3}$ 990	25–55 ($w = 350$ m)
6 Gravel dominated, stable		Southern Ind., USA	Miller (1991)	Humid temperate, cold winters	Dissected and forested hill country	Storms and snowmelt	Q_b 10–30	100–200

Sediment load	Bed material	Bank material	Sinuosity	Gradient ($m\,m^{-1}$)	w/e	Levees	Vertical activity ($mm\,yar^{-1}$)	Lateral activity
30% as bed-load	Medium sand $D_{50} \sim 0.42$ $D_{90} \sim 0.72$	Medium and fine sands	Low 1·1	0·0005	~ 10 (mean)	Prominent 0·5–1·5 m high	~ 15	Little or no migration, some crevassing
–	Sand/gravel	Silt-clay	2·5	0·0011	15	Prominent alluvial ridge	–	Alternating between stable and active
–	Gravel	Mixed silt and sand	1·3	0·0020	40	None	–	
~ 5%	Sand	Silt and clays over sand	1·5	–	–	–	–	Laterally active
Mixed load	Sand and gravel	Silt and clay over sand and gravel	1·3–2·5	0·00035	–	None	–	Laterally active
Probably bedload dominated	Medium sand	Medium and fine sand and organics	1	0·0005–0·0009	10	Subdued	Stable	Stable
–	Medium sand	Sand and mud	1·1	0·0006	25–80	None	Stable	Stable
Sand dominated	Sand	Sand and mud	1·1	0·002	12–25	None	Stable	Stable
–	Gravel	Basal gravels 2/3 of the section; upper 13 sand	1·2–1·4	0·0019–−0·0033	50–122	Not significant	Local aggradation in anabranching reaches	Active in unstable reaches
–	Gravel	Basal gravels and overlying sand	1·2	0·0012	–	Not signficant	Stable	Moderately active
Gravel dominated	Gravel	Basal gravels and overlying sand	1·1	0·0025	85	–	–	Slightly active
Gravel dominated	Gravel	Gravel over-lain by silt	1·4	0·00094	46	–	Stable	Slightly active
Gravel dominated	Gravel	Gravel over-lain by silt and sand	1·3	0·0015	–	–	–	Moderately active
Gravel dominated	Gravel	Gravel over-lain by silt and sand	1·1	0·001–0·002	–	–	–	Moderately active
Gravel dominated	Gravel	Upper silty sand, lower gravel	1·1–1·3	0·01–0·025	6–16	$\leqslant$0·3 m	Stable	Stable

Table 1

Type	Sub-type	River	Reference	Climate	Physio-graphic setting	Flow regime	Discharge ($m^3 s^{-1}$)	Specific stream power ($W m^{-2}$)
		Barrier Range, Australia	Dunkerley (1992)	Hot, arid	Desert uplands	Arid, ephemeral	Q_b 350–680	80–150

Q = mean annual discharge; Q_b = bankfull discharge; Q_2 = median annual flood; $Q_{2.3}$ = mean annual flood; D_{50} = median grain size

(a) Organic systems. The only system of this type to be described in detail is the Okavango megafan in Botswana (McCarthy *et al.*, 1988, 1991, 1992). It accumulates a 'floodplain' largely of organic mater formed *in situ* or sieved by aquatic plants from organic debris washed down the river. The channels are characterized by fine sandy bedload and very little suspended load (McCarthy *et al.*, 1991). Aggradation of bedload and the concomitant growth of aquatic vegetation constricts channel flow, inducing periodic avulsion. In the case of the Okavango, the rapidly accumulating peats are periodically destroyed by fire, restricting the ability of the overall system to vertically accrete. In a system free of fire, the stratigraphy would consist of vertically accumulating channel sands and adjacent peats (Figure 3A).

(b) Organo-clastic systems. These consist stratigraphically of both clastic and organic sediment, the latter sometimes in the form of peat interbedded between clastic units of channel, splay and fine overbank sediment (Figure 3B). Resistant, well-vegetated banks (Smith, 1976) protect swampy, levee-banked islands commonly with central depressions that may produce lacustrine sedimentary facies. Initially termed 'multimeandering systems' by Smith (1973), these have been described in detail by Smith (1973, 1983) and Smith and Smith (1980) for short reaches of partially obstructed gradient-reduced valleys in the Rocky Mountains of Canada. Although transporting a bedload of sand and sometimes gravel, they are characterized by abundant overbank fine-sediment deposition and organic accumulation on what are commonly rapidly accreting low-gradient floodplains (Figure 3B). Similar, but much larger swampy systems have been described by Smith (1986) for a subsiding foreland basin in Colombia, and by Smith *et al.* (1989) for a Pleistocene glacial-lake plain in Canada. Harwood and Brown (1993) describe a small, stable, forested system in Ireland where, due to relatively little sediment load, vertical accretion is not significant. Similar systems may have been much more widespread in Europe prior to forest clearance and channel works (A. Brown, pers. comm., 1993). Because most of its characteristics conform, the Attawapiskat River in Canada is included in this subtype, even though it is incising rather than vertically accreting (King and Martini, 1984), possibly due to relatively rapid postglacial isostatic rebound.

(c) Mud-dominated systems. These are mud-dominated, low-gradient anastomosing channels only slowly accreting (Figure 3C). They have been described for the Channel Country, a semi-arid region of east-central Australia where the Diamantina River and Cooper Creek anastomose over 600 km of their length and across floodplains up to 60 km wide (Figure 4) (Nanson *et al.*, 1986, 1988: Rust and Nanson, 1986). A similar system occurs on a much smaller scale in the Red Desert of Wyoming (Schumann, 1989). Very little bedload is transported, and the channel banks and floodplains are composed almost entirely of very cohesive clastic mud (Figure 3C). Of all anabranching systems, it would appear that these are least influenced by vegetation which, in the above examples, is relatively sparse.

Schumann (1989) proposes a sequential mechanism of channel initiation by avulsion, and atrophication of the older channels through progressive infilling with mud. Periodic avulsion is the primary means of rejuvenation and lateral mobility in these stable systems, but it appears to occur very infrequently.

Type 2: sand-dominated, island-forming anabranching rivers

Because of the generally non-cohesive nature of sand, this type requires the combination of stabilizing

Sediment load	Bed material	Bank material	Sinuosity	Gradient (m m^{-1})	w/e	Levees	Vertical activity (mm yar^{-1})	Lateral activity
–	Gravel	Upper fines, lower gravels	Low	0·004	30–60	Not signficiant	Stable	Stable

bank vegetation and low stream energy to prevent the channel from braiding or meandering. Stratigraphically, they are sand-dominated, with finer sands and silts near the floodplain surface (Figure 5A). Specific stream powers are commonly 4–8 W m^2 and sinuosities are very low. In terms of discharge and slope, they plot in the same general location as type 1 channels (Figure 1) (Knighton and Nanson, 1993), yet their sediments are much less cohesive and their channels tend to be subparallel with intermittent, relatively wide and sometimes braided reaches, the latter commonly with trees growing on the channel bed. Following the nomenclature adopted by Church (1983) for certain gravel rivers, these could be termed 'wandering sand-bed rivers'. However, in contrast to their gravel counterparts, anabranch stability in sandy alluvium requires low specific stream powers and dense tree roots extending to the base of the banks.

The only example studied is Magela Creek, located in the monsoon tropics of northern Australia (Nanson *et al.*, 1993), although numerous similar rivers exist in the area. Magela Creek commonly experiences bankfull flow many times during each wet season but, in contrast to most rivers, the 2–3 year flood event is about ten times the magnitude of bankfull flow (Roberts, 1991). However, even during major floods, erosive energy remains low (specific power $\leqslant 12\,\mathrm{W\,m^{-2}}$) because of the relatively low gradients. Under such conditions, both streamflow and bed-material sediment load are concentrated along relatively narrow and deep channels rather than spread over less efficient, wider and shallower channels that are partially obstructed by trees growing on the bed.

It is not clear whether the islands form by vertical accretion in wide sections of channel or by separation from the extant floodplain by channel avulsion, but channel avulsion is evident on parts of the floodplain. The creek is silt-starved, due to geological provenance, dominated by sandy bedload and has very little fine sediment in the floodplain (Roberts, 1991). Riparian forest appears to be essential for lateral stability, without which the channels would probably braid.

Type 3: mixed-load, laterally active anabranching rivers

These are meandering multichannel rivers that migrate laterally across a portion of their floodplain. As with meandering rivers generally, they represent a diverse group that are difficult to define as a single type, carrying a mixed sediment load of sand and mud and, in some cases, fine gravel. Brizga and Finlayson (1990) have described the Thompson River in southeastern Australia, which oscillates between energy states when forming short-lived anabranches. Following channel avulsion associated with a major flood, a laterally active channel forms with specific stream powers at bankfull of about 50 W m^{-2}. Gradually, this system atrophies to form a sinuous, relatively inefficient channel, with specific power of 5–10 W m^{-2}, before avulsing to form a higher energy channel again (Figure 2). To what extent this sudden increase in stream power is characteristic of most recent anabranches, not just within type 3 rivers, is not known.

In an ongoing study, Erskine (pers. comm., 1994) and Schumm have identified anabranches of the Murray River in southeastern Australia that are also laterally migrating but where the anabranches are very long-lived. In both the Thompson and Murray examples, the floodplain near the main channels is formed of sandy lateral-accretion deposits, but distal to these are abundant fine-grained overbank deposits (Figure 5B). Still poorly understood stratigraphically, the resulting floodplain appears to be similar to that of the laterally

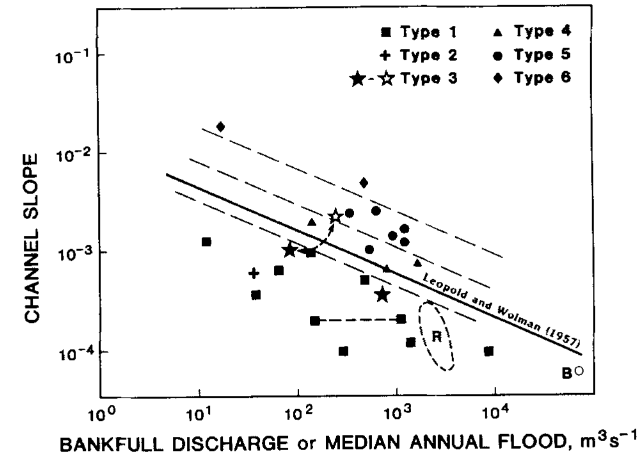

Figure 1. Distribution of the six types of anabranching rivers on a slope–discharge plot. Included is the line dividing those channels that Leopold and Wolman (1957) described as meandering (below) and braided (above). On the basis of stream power, the parallel dashed diagonals roughly separate anabranching rivers into four groups (types 1 and 2; type 4; type 5; and type 6). A dashed arrow links the alternating condition of one of the type 3 systems (the Thompson River (Brizga and Finlayson, 1990)), and the horizontal dashed line links the upstream (high discharge) and downstream (low discharge) gauging stations of Cooper Creek (Knighton and Nanson, 1994). B represents the Brahmaputra River (Bristow, 1987) and R delimits the distribution of conditions exhibited by the Rapti River (Richards *et al.*, 1993), both part of the Indogangetic Plains

active single-channelled Fly River in Papua New Guinea, which is forming a floodplain of overbank deposits distal to the channel (Blake and Ollier, 1971). In many respects type 3 rivers are similar to type 1b, although laterally more active.

Type 4: sand-dominated, ridge-forming anabranching rivers

Not yet described in the literature, these linear and curvilinear ridged systems have been observed by the

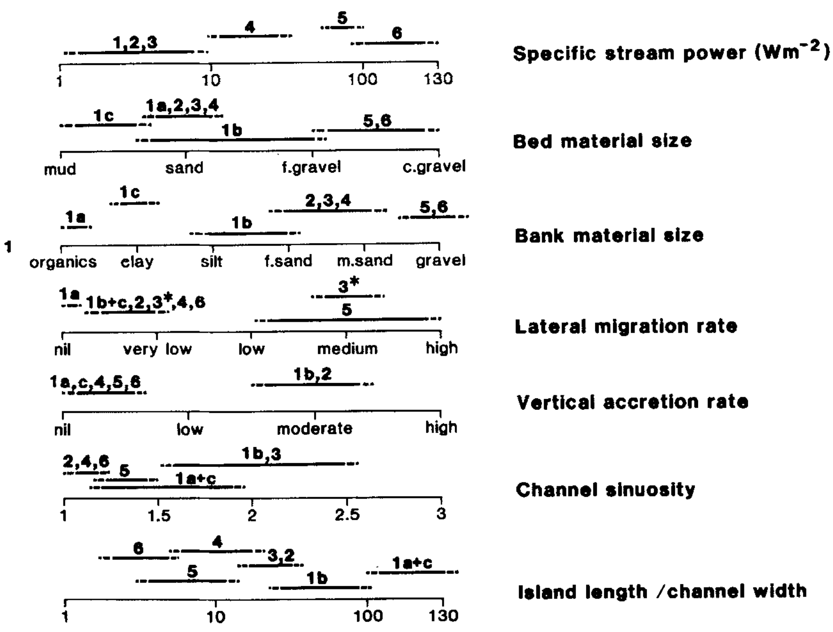

Figure 2. The approximate distribution of specific stream power, bed texture, bank texture, lateral migration rate, vertical accretion rate, channel sinuosity and island length/channel width ratio for each of the eight anabranching types and subtypes. Type 3* is sometimes characterized by an alternating condition between two very different rates of lateral migration (see Figure 1) and its rate of vertical accretion is not known

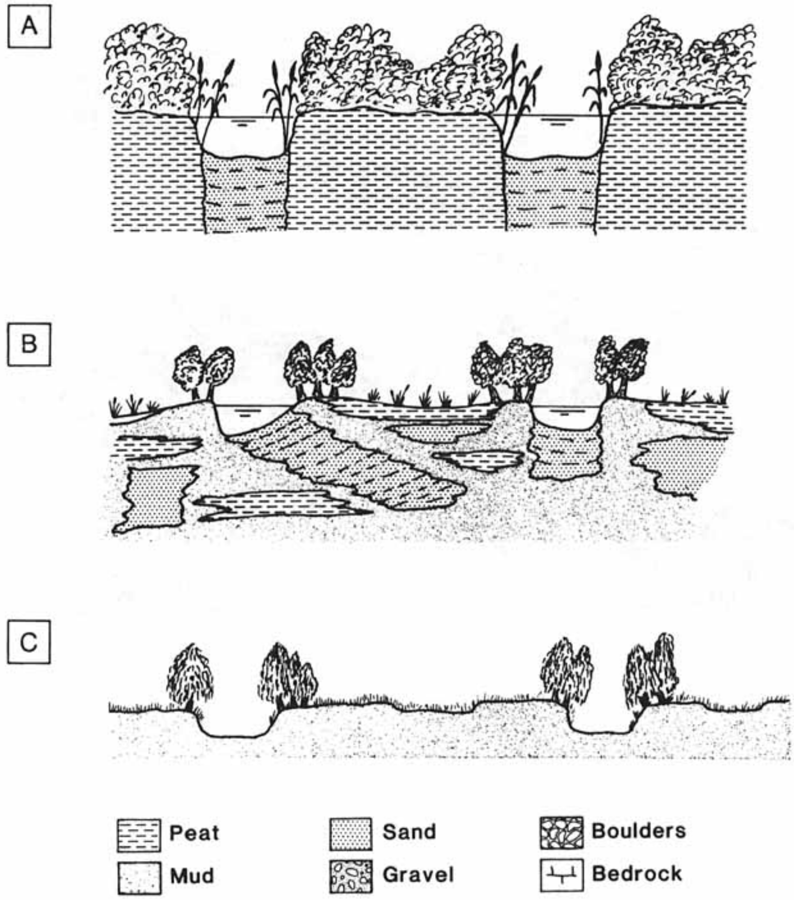

Figure 3. Cohesive sediment anabranching rivers: (A) organic systems (type 1a); (B) organo-clastic systems (type 1b); (C) mud-dominated systems (type 1c)

first author in the Kimberley region of Western Australia and immediately upstream of 'floodouts' (extensive alluvial sheet-deposits essentially devoid of channels) in central Australia. In both locations they are presently the subject of detailed investigation. They are considered in somewhat more detail here than the other types because of the lack of alternative sources, and because they provide information important for understanding anabranching in general.

In the Kimberley examples, the total channel and ridge system is confined by bedrock and sometimes indurated alluvium (R. Wende, pers. comm., 1994), whereas in central Australia the confining medium is commonly cohesive muds (S. Tooth, pers. comm., 1994). Although flanked by alluvium, exposures of bedrock on their beds indicate that they are not vertically accreting. Channels with low width/depth ratios (20–30 m wide) are separated by narrow, steep-sided sandy ridges (2–4 m high, 10–30 m wide and 50–1500 m long) topped with lines of stabilizing trees (Figure 5C and 6). These ridges commonly form in wide sandy channels as the result of within-channel tree growth acting as an obstruction to flow. Lee-side deposits extend linearly downstream, with one tree providing protection for the next to establish and so forth, and they maintain their continuity even though curving through valley bends (Figure 6). The result is a wide sandy channel converted to a system of multiple flow compartments separated by narrow ridges that eventually reach approximately the floodplain height (Figure 5C). On the Woodforde River in central Australia, similar long, straight channels and narrow intervening ridges appear also to form by channel avulsion and excision from the floodplain (S. Tooth, pers. comm., 1994).

Stream powers are significantly higher (15–35 W m^{-2}) than for the otherwise similar type 2 streams, hence the formation of streamlined ridges rather than islands. Their subparallel, almost linear channels, which do

Figure 4. Aerial view of Cooper Creek, central Australia (type 1c). The large channel in the foreground is ~ 20 m wide

not bifurcate or join for considerable distances, make these systems distinctly different from braided rivers, which have higher gradients and stream powers, and mobile and ephemeral within-channel bars. Vegetation is essential for without the trees, the sandy ridges would disintegrate during floods.

The persistence of numerous parallel ridges over many kilometres of channel in parts of central and

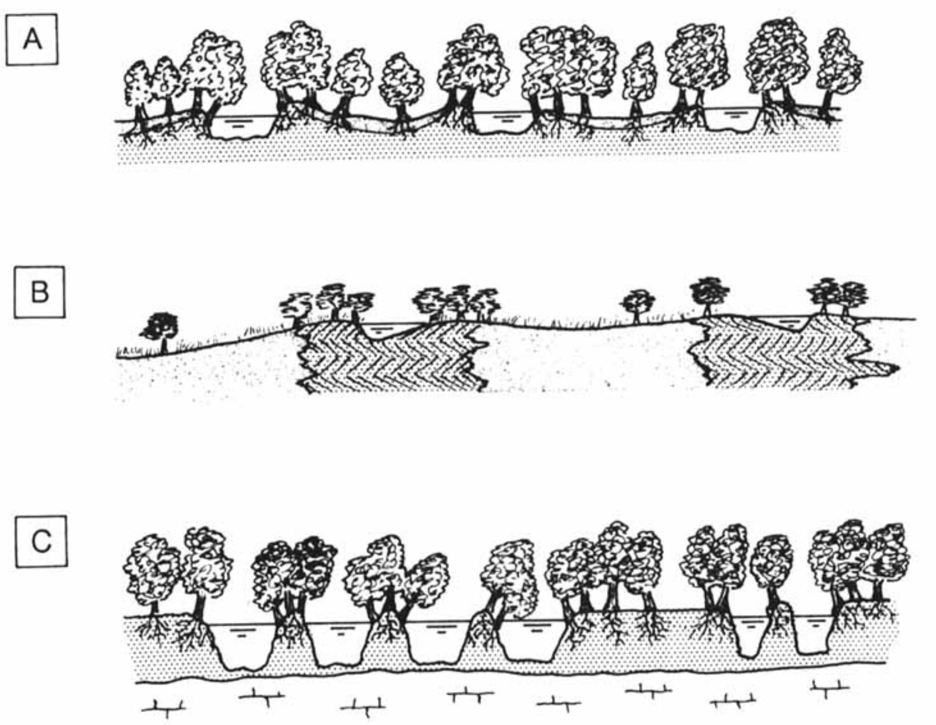

Figure 5. (A) Sand-dominated, island-forming system (type 2); (B) mixed load laterally active system (type 3); (C) sand-dominated, ridge-forming system (type 4)

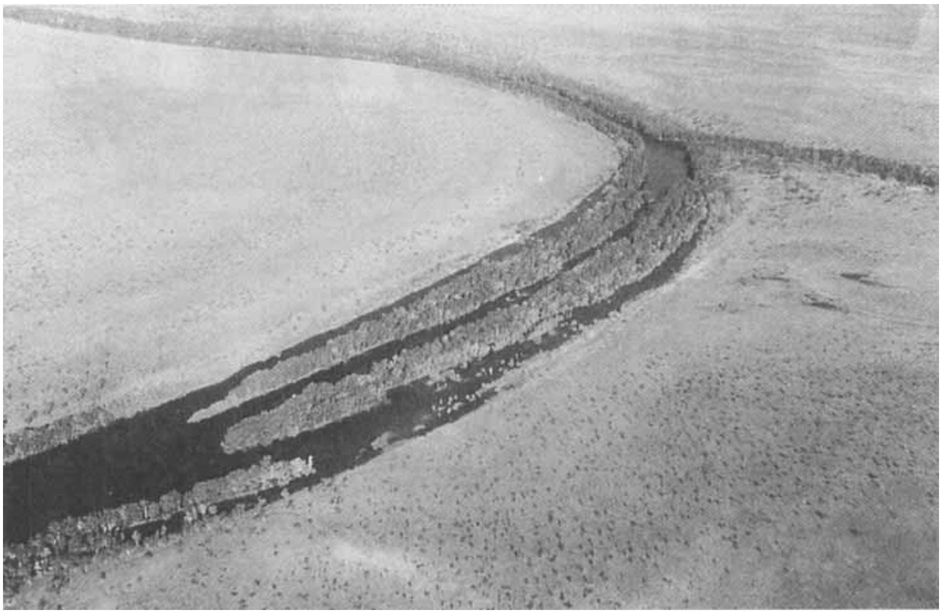

Figure 6. Aerial view of the Durack River in the Kimberley region of northern Australia (type 4). The distance across the channels and ridges combined is ~ 350 m

northern Australia must mean that this is the most stable channel form generally in equilibrium with local conditions. Because these rivers must move sand along low-gradient valleys, they cannot become sinuous or braided as this would diminish their energy gradients and add distortion resistance through bends and around bars. The formation of straight but wide and shallow sandy channels would result in relatively low bed shear stress and specific stream power. Instead, the construction of substantial alluvial ridges confines the flow into a series of relatively straight, subparallel, narrow and deep channels, maximizing these force and energy terms and ensuring the onward transport of sandy bedload. The phreatophytic vegetation, which elsewhere often grows in a somewhat chaotic fashion within the channels of ephemeral rivers of arid Australia, is here distributed linearly on the ridges, maximizing the strength of these features and further reducing distortion resistance within the flow.

These type 4 rivers have a higher stream power and hence are a more streamlined variant of type 2, for both are strongly dominated by sand deposition along ephemeral streams where riparian vegetation is crucial for developing non-compliant banks.

Type 5: gravel-dominated, laterally active anabranching rivers

These are relatively energetic wandering gravel-bed rivers that Church (1983) and Desloges and Church (1989) describe as transitional between meandering and braiding (Figures 7A and 8). They often exhibit a dominant channel accompanied by several anabranches, but may also alternate downstream between multi- and single-channelled reaches. The dominant channel commonly braids (Figure 8) (Carson's (1984) wandering type 2 system). Specific stream power varies from about 30 to 100 W m^{-2}, hence there can be vigorous lateral activity which, on the Bella Coola River of British Columbia, has replaced the floodplain about once every 300 years (Desloges and Church, 1987). In the last century, substantial reaches of this river have changed from a laterally unstable anabranching river with large forested islands (Figure 8), to a more stable, single, sinuous but migrating river (Carson's (1984) wandering type 1 system), probably as a result of the reduction of bed-sediment supply (Church, 1983). Within these systems, minor anabranches can be very stable. The anabranching sections of these rivers appear to be initiated by enhanced bed-sediment input, displacing the flow into a series of anabranches, and the periodic formation of log or ice jams may augment this process. In this case, too, it appears that anabranching is driven by the need to maintain the transport of bed

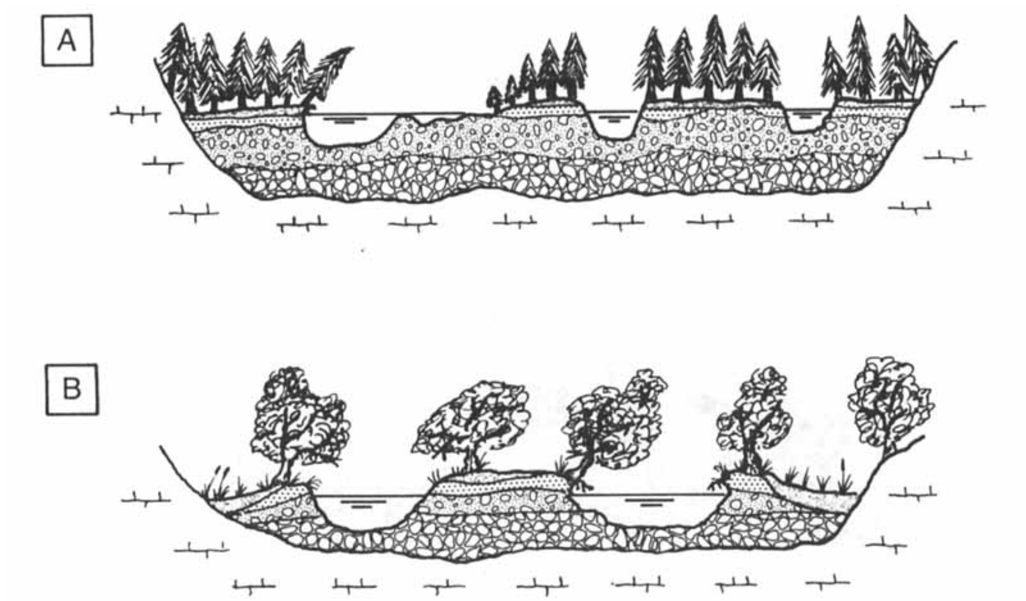

Figure 7. (A) Gravel-dominated, laterally active system (type 5); (B) gravel-dominated stable system (type 6)

material in conditions where this fraction of the load might otherwise accumulate (Knighton and Nanson, 1993).

Avulsion channels incise into existing floodplains, but in some cases islands grow vertically to floodplain height from large bars stabilized by vegetation within the channel (e.g. on the Fraser River near Mission, British Columbia; M. Church, pers. comm., 1993). Stratigraphically, the floodplains consist of a basal

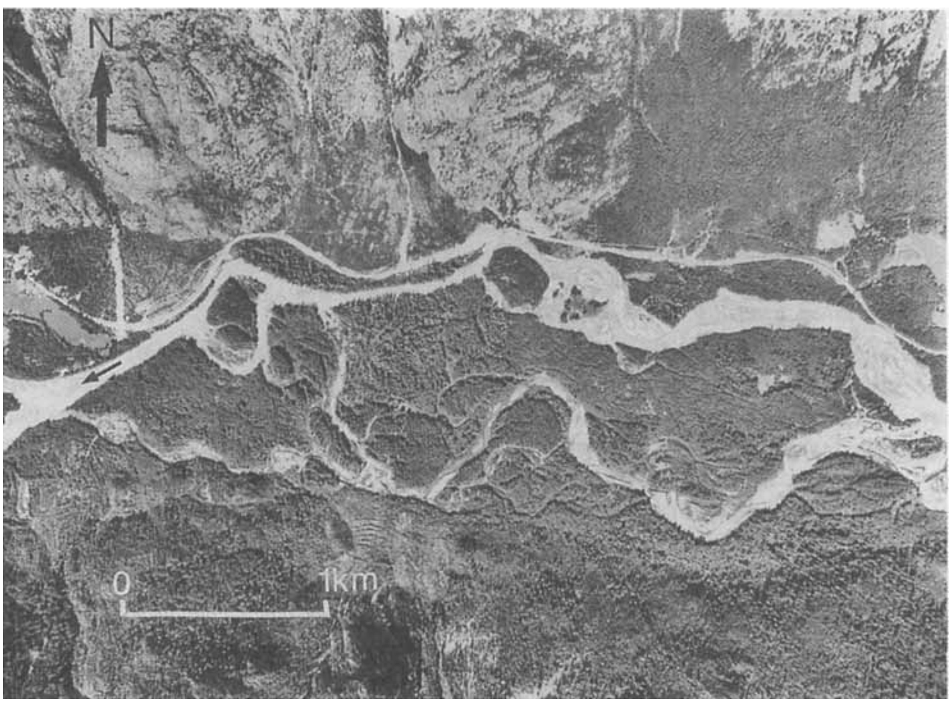

Figure 8. Aerial view of the Bella Coola River, British Columbia (type 5) (Photo BC82040/071, August 1982)

unit of gravel with overlying channel and overbank sands and silts (Figure 7A) (Desloges and Church, 1987; Brierley and Hickin, 1992).

Type 6: gravel-dominated, stable anabranching rivers

A number of small, steep drainage basins that respond to rapid rainfall events exhibit anabranching channels with well-vegetated gravel, coarse-gravel or boulder islands (Figure 7B). They have been described in detail for sets of small drainages (4–$\leqslant$10 km^2 in area) of forested upland in southern Indiana (Miller, 1991) and in the desert streams of the Barrier Range in NSW, Australia (Dunkerley, 1992). Because of their steep gradients they can exhibit relatively high stream powers (100–300 W m^{-2}). However, very bouldery alluvium or finer gravels held together by tree roots ensure channel stability; where they are formed of finer cobble sizes, they are able to do so because of the formation of coarse lag-cobble surfaces relatively close to the source of material. The means by which anabranches are formed appears to be similar to type 5, log jams and/or sediment accumulation being the major causes.

THE DISTINCTIVENESS OF TYPES

Slope–discharge relationships are now commonly used to differentiate river pattern type. One of the first and best known of these analyses was by Leopold and Wolman (1957). They attempted to separate meandering from braided rivers, but their latter group consisted of a variety of anabranching systems (with semi-permanent islands) with relatively few truly braided rivers. This confusion highlights the need for an examination and classification of anabranching systems, as is undertaken here.

In more recent work, Church assembled additional data on a wide range of meandering and truly braided rivers (published in Kellerhals, 1982; Ferguson, 1984; 1987; and Church, 1992), demonstrating that bed-material grain size is a major factor determining river pattern. Carson (1984) also argues that the meandering/braiding threshold is essentially a grain size transition, concluding that gravel-bed streams are more likely to be braided than channels in finer sediment. Although quantitative data on grain size are not available in all instances, the general trend identified here supports the contention that specific stream power (or alternatively, bed shear stress) and hence sediment size can be used as important preliminary discriminators of river type.

The eight types and subtypes described above are categorized on the basis of stream power and distinctive morphologic characteristics such as planform and island shape. When all are plotted on a slope-discharge relationship, a recognizable differentiation is apparent (Figure 1). Types 1–3 plot with relatively low stream powers (broadly equivalent to the product of slope and discharge) and mostly below the line defined by Leopold and Wolman (1957) differentiating meandering from what they termed braided rivers. Types 5 and 6 plot higher (Figure 1) and type 4 forms an intermediate category. Of note is that type 3 rivers can shift their position from lower to higher energy as they alternate from older, sinuous channels to recently avulsed, more energetic ones (Brizga and Finlayson, 1990); however, this may also be true of other types that have recently avulsed. With some overlap between adjacent types, Figure 1 suggests that anabranching systems operate across a continuum of stream powers from low to moderately high, but an inspection of morphological characteristics indicates that they can be separated into at least eight reasonably distinctive types and subtypes within this array.

COMMON CAUSES AND CHARACTERISTICS

The vast majority of rivers flow in a single channel, for even braided rivers characteristically flow between a dominant pair of floodplain banks (Reinfelds and Nanson, 1990). Anabranching rivers are probably sufficiently uncommon to suggest that they result from an unusual set of flow and sediment-load conditions, albeit in a wide range of climatic, sedimentary and energy environments. Furthermore, because anabranching is frequently not spatially or temporally persistent (Smith, 1973; 1983; Smith and Smith, 1980; Church, 1983; Carson, 1984; Brierley and Hickin, 1991, 1992), it would appear that certain very specific conditions may control the process.

The mechanisms that actually produce multiple-channel systems appear to be a response to two sets of fundamentally different processes.

(1) *Avulsion (erosion)-based processes:* (i) the scouring of new channels into the floodplain (first-order avulsion), and (ii) the reoccupation of old channels on the floodplain (second-order avulsion).
(2) *Accretion-based processes:* (i) channel extension into a depo-basin such as with a prograding delta or infilling estuary, and (ii) the accretion of within-channel bars to form islands or ridges that divide clearly separated channels. While not the topic of this paper, it is worth noting that deltas and estuaries often develop relatively permanent anabranching channel systems from their inception. Subaqueous bars in a prograding delta or in wide channels evolve into subaerial bars and eventually into semi-permanent islands.

The breaching or crevassing of levees has been widely observed to initiate anabranch development in accreting systems (Smith and Smith, 1980; Smith, 1983). Popov (1962) argued that floodwaters can scour secondary channels on low-relief areas of the floodplain and that these channels can enlarge and capture some or all of the flow from the main channel, a process that does not require aggradation. Schumann (1989), Brizga and Finlayson (1990), and Miller (1991) have observed essentially this process in a range of accreting and stable situations, with avulsion often associated with gully incision and headcutting. In a study of the Mississippi delta, Fisk (1952) suggested that an anabranch can develop if the main channel migrates laterally and intersects a floodplain drainage channel (or palaeochannel) which, if the latter has a gradient advantage, will probably scour and capture additional flow. Smith *et al.* (1989) propose a cyclical process whereby an initial large-scale channel avulsion leads to an anabranched system which may revert to a single channel, before repeating the cycle.

Apart from multiple channels, anabranching rivers as a group appear to have remarkably little in common (Table I and Figure 3). Individual channels can be braided, actively meandering or laterally stable and straight. Bedload can vary from less than 1 per cent of the total solids load, as in the case of the Fraser River near Mission in British Columbia (M. Church, pers, comm. 1992), to about 30 per cent along Magela Creek in Australia, to about 50 per cent on the anastomosing middle and lower portion of the Okavango megafan. The concentration of bed material in transport is probably much more important than the percentage bedload, which is statistically dependent on the proportion of fines in transport, but this is very rarely reported. Suspended load concentrations tend to be very low on those rivers with measured data (King and Martini, 1984; McCarthy *et al.*, 1991; Roberts, 1991) but are probably relatively high during flood stages on the alpine and glacially fed streams that form extensive floodplains of fine sand and silt (e.g. Smith and Smith, 1980). While some have rapidly vertically accreting floodplains (Magdalena, Saskatchewan, Alexandra, and Columbia Rivers), this is certainly not a requirement for anabranching. For instance, Cooper Creek is accreting very slowly (Table I). Those studied in Indiana (type 6; Miller, 1991) appear to be relatively stable and in the longer term may be gradually incising into a bedrock substrate, as do type 4 streams in the Kimberley region of Western Australia. The Attawapiskat River of James Bay, Canada, is clearly an incising anabranching system on an isostatically rebounding landscape (King and Martini, 1984).

The importance of vegetation for stabilizing the banks is difficult to assess in every case. It is certainly very important on the Okavango megafan (McCarthy *et al.*, 1991), on the North Saskatchewan River (Smith, 1976) and in the type 2 and type 4 sandy systems of northern and central Australia. The stability of islands in the type 3 anabranching channels of the Amazon basin are attributed by Baker (1978) to rapid plant colonization. However, in the Channel Country of western Queensland, type 1c systems with cohesive muddy banks are often lined with well-spaced trees that lack an understorey or a dense network of roots. The gravel-dominated laterally active rivers (type 5) are probably least aided by bank-stabilizing vegetation, for the vegetation root mat does not extend down to and protect the lower parts of these river banks.

The above discussion makes it possible to identify the conditions that are not especially important for the formation of anabranches (abundant bedload, abundant suspended load, vertical accretion, abundant bank vegetation), and to isolate those that probably are. From a consideration of all the river systems described in Table I, it appears that the dominant factors that commonly operate in unison are, firstly, a highly variable flood-prone flow regime, and secondly, banks that are erosionally resistant relative to stream power.

Mechanisms for periodically displacing a large proportion of the channel flow to overbank flow across the floodplain may also be involved.

Variable flooding

A highly seasonal or extremely episodic flow regime is characteristic of all the rivers in Table I, although lack of suitable data prevents calculation of a quantitative flood-variability index. Amongst the low-energy systems, the aquatic and highly organic Okavango megafan experiences annual flooding due to tropical summer rain, and about one-third of its area remains permantly inundated (McCarthy *et al.*, 1991). Cooper Creek, in semi-arid central Australia, does not flood every year, but compared to other rivers, flood magnitudes at modest return periods are very large (Knighton and Nanson, 1994). The Columbia, Saskatchewan and Alexandra Rivers of North America have highly seasonal snow-melt regimes that are ponded over low-gradient floodplains (Smith, 1973, 1983; Smith and Smith, 1980) and the Magdalena River in tropical South America experiences a bimodal flood peak, also inundating a low-gradient floodplain for a prolonged period (Smith, 1986). Of the three adjacent rivers studied in the Amazon basin by Baker (1978), the two with highly variable flows anabranch (type 3) whereas the one with relatively uniform flow does not. Magela Creek (type 2) in the Australian tropics is dry for half the year but experiences frequent overbank flows during the remaining half (Roberts, 1991), as do those in the Kimberley of Western Australia (type 4). The gravel-dominated, laterally active rivers of Canada (type 5) are highly seasonal and fed by snow-melt (e.g. Kellerhals *et al.*, 1972; Church, 1983). However, as there are many rivers with highly variable flow regimes that do not anabranch, so other conditions must combine to result in the development of multiple channels.

Resistant banks

Bank resistance is relative to specific stream power or bank shear stress, and its influence on channel pattern can be greatly affected by the stabilizing effect of bank vegetation (Smith, 1976; Hickin, 1984). The banks of type 2 and type 4 streams are largely sand, but the stabilizing vegetation in combination with relatively low stream power results in their lateral stability. However, vegetation is an important contributor to bank stability on rivers with relatively shallow alluvium only where the root mat extends to the base of the bank, or in those systems dominated by frequent low flows where vegetation can extend to near the base of the channel banks. Resistance to bank erosion controls channel migration rates (Hickin and Nanson, 1984) and limits the ability of the channel to progressively reform and adjust to temporal and spatial changes in flow and sediment conditions. The relatively resistant aquatic vegetation on the Okavango megafan, and the cohesive muds of the North and South American and central Australian examples, retard channel migration and encourage the development of canal-like multichannel systems. The combination of frequent or high-magnitude flooding in channels that cannot readily alter their capacity is a precondition for avulsion and the formation of new channels elsewhere on the floodplain.

Flow displacement

A highly variable flow regime within a constrained channel will result in frequent overbank flow and sometimes channel avulsion. However, other, more specific mechanisms may be instrumental in displacing flow from the channel: channel sedimentation; the formation of vegetation or ice jams; and ineffective flow (ponding or hydraulic damming) due to very low channel gradients or entry of a major tributary.

Channel sedimentation. Not necessarily related to vertical floodplain accretion discussed above, this commonly results from an excess of bedload supply relative to the ability to maintain onward transport, a point recognized by Knighton and Nanson (1993) in their evaluation of anastomosing systems. The Bella Coola River appears to anabranch in certain reaches due to locally enhanced sediment deposition (Church, 1983). On the Magdalena River, nearly 40 per cent of the incoming sediment load is deposited in its anastomosing reach, whereas the Columbia River deposits about 55 per cent of its bedload where it anastomoses and is characterized by crevasse splays (Smith, 1986). On the Okavango megafan, bedload is being deposited in channels at a rate of up to $5\,\mathrm{cm\,a^{-1}}$ (McCarthy *et al.*, 1991). In some cases, anabranching channels constrict as a result of suspended load deposition in the form of benches along the channel margins, which eventually displace flood flows into anabranches (Taylor and Woodyer,

1978). In meandering or braided rivers, channel sedimentation can readily be accommodated by lateral migration and associated modification of channel dimensions. However, low-energy anabranching (anastomosing) channels have insufficient energy relative to bank strength to permit such adjustments to reducing channel capacity, hence avulsion is more likely to occur.

Vegetation jams or ice jams. While channel sedimentation is usually a gradual process, log or ice jams can be almost instantaneous (Smith *et al.*, 1989) and may act as 'triggers' in a system already prone to anabranching. The anabranching snow-melt channels of North America are commonly obstructed by log (Hickin, 1984) or ice jams that back up the flow until the levees are eventually overtopped and a floodplain splay or avulsive channel is formed (Smith, 1983). Similar obstructions, but formed of soft aquatic vegetation, occur on the Okavango megafan (McCarthy *et al.*, 1991, 1992), whereas individual trees can obstruct the flow in small-scale anabranching systems (Harwood and Brown, 1993).

Ineffective flow (ponding). In a number of very low gradient systems, avulsion may result, not because of exceptional channel sedimentation or constriction by vegetation or ice jams, but because low channel velocities overlow gradients act to 'dam' the channel (Riley, 1973). After exceptional rain, parts of western New South Wales and central Australia take on the appearance of a vast lake that can remain for weeks. Under these conditions, and as a result of localized scour particularly during the rising stages of a flood, new channels can be gradually excavated into the floodplain surface. Some channels atrophy downstream, indicating declining flow efficiency in that direction. Even at well above bankfull flow, downstream velocities in the largest channels of the Cooper system of central Australia do not exceed $0{\cdot}8\,\mathrm{m\,s^{-1}}$ and are commonly only $0{\cdot}1$–$0{\cdot}2\,\mathrm{m\,s^{-1}}$ in the smaller channels, with exceptionally low sediment transport rates (Nanson, unpublished data). Channels on the Okavango megafan in Botswana exhibit similarly low velocities, and flooding is even more persistent (McCarthy *et al.*, 1988).

Tectonism

In some cases, tectonism (backtilting or basin subsidence) can set in place conditions that will lead to anabranching (Burnett and Schumm, 1983; Gregory and Schumm, 1987). Rather than essential in itself, it can lead to reduced stream gradients, increased channel sedimentation, flow displacement and avulsion, which are the proximate causes.

THE ADVANTAGES OF ANABRANCHING; DIVIDE AND CONQUER

A river in a state of dynamic equilibrium adjusts its channel pattern, cross-sectional geometry, slope and roughness in order to balance the available sediment load with an ability to transport this load. The temporal and spatial persistence of anabranching systems indicates that in certain situations they must exhibit considerable advantages over their single-thread counterparts.

Braided rivers can adjust to increased bed-sediment discharge/water discharge ratios by increasing their gradients, as do meandering rivers by reducing their sinuosity. Under conditions where gradients cannot be increased, or indeed where they may have been locally reduced, and where lateral migration is restricted or prevented, then an increase in the sediment/water discharge ratio must be accommodated by an increase in the rate of work being done per unit area of the bed.

Anabranching is commonly associated with deltas (e.g. King and Martini, 1984), valley obstructions (Smith, 1973, 1983; Smith and Smith, 1980), tectonic tilting (Burnett and Schumm, 1983; Gregory and Schumm, 1987), subsiding basins (Smith, 1986) and low-gradient inland basins (Nanson *et al.*, 1986; Rust and Nanson, 1986); Smith *et al.*, 1989), all environments where water and/or sediment throughput must be maintained with little or no recourse to increasing energy gradients. In some relatively high-energy Canadian rivers, the need for enhanced bed-sediment throughput appears to trigger anabranching (Church, 1983).

It is proposed here that, in contrast to a wide single channel which commonly has mid-channel bars and possibly channel vegetation, the major advantage of an anabranching system is that work done can be concentrated into several narrower, deeper and relatively unobstructed channels. If the net effect of anabranching is to reduce the total bed width and increase the average depth and velocity,then this will increase specific stream power and bed shear stress without increasing slope (e.g. Chang, 1979b). In terms of total sediment

discharge, any reduction in total bed width resulting from the formation of islands would be more than compensated by the increased transport rate. Colby's (1964) study of sand-bed streams demonstrates that, within the range of most alluvial streams, sediment discharge per unit bed width increases as approximately a cubic function of bed shear stress or specific stream power. Using Colby's relationships, a hypothetical single-thread reach converting into multiple channel with no change in slope, channel roughness and water discharge, but with a 20 per cent reduction in total bed width due to the introduction of dividing islands, can be shown to yield an increase in the overall sediment throughput. However, the exact extent of this increase cannot be resolved in a simple model because of the indeterminant nature of channel geometry adjustments. In reality, improved sediment transport may be slight, merely sufficient to maintain the continuity of sediment throughput and therefore not enough to cause the anabranching reach to incise or become instable. From an assumption that rivers operate in an equilibrium condition when total stream power is at a minimum, Chang (1979b) shows that the relationship between total stream power and channel width may be very complex, with some systems exhibiting more than one equilibrium width, a condition that may be particularly relevant to anabranching systems. Further work should attempt to model this, comparing measured data from adjacent single-thread and anabranching reaches.

In systems with a very low sediment flux, maintaining a throughput of sediment may not be a particular problem. In the Channel Country of Australia, anabranches move large water discharges through very low gradient basins over floodplains tens of kilometres wide in a system of channels more hydraulically efficient than shallow overbank flow (Knighton and Nanson, 1994). In this situation, the anabranching network of channels reduces flow resistance and enhances water throughput.

In summary, therefore, anabranching appears to be a mechanism whereby a river can enhance or maintain its water and sediment flux without increasing channel gradients. They divide and concentrate their flow, thereby conquering a diminishing capacity to transport sediment; however, this can only occur where stream banks are relatively cohesive and can resist increased stress.

ANABRANCHING AND THE PROBLEM OF RIVER CLASSIFICATION

In geomorphology, classification can be used to identify common processes and morphologies, separate disparate ones, and thereby assist in understanding the causal relationships between form and process. Regardless of what procedure is adopted, any classification of rivers based primarily on planform is not ideal, because planform is only one variable in a complex array of fluvial processes and resulting morphology. Nevertheless, it is a useful first step.

A significant problem faced in classifying rivers is that the basic terminology is imprecise. A distinction is made here between 'river pattern', which is used to describe the planform geometry and to imply the processes operating within a reach of river, and 'channel pattern', which is limited to defining these characteristics within an individual channel. This distinction is useful where a river anabranches but contains a variety of channel patterns. The term 'planform' is used to denote the plan geometry without reference to any particular processes. It is also useful to distinguish between meandering and stable-sinuous patterns. The former are systems that have a sinuous planform and that are actively migrating and forming floodplains by lateral accretion, and the latter are those that have a sinuous planform but are essentially stable, with a floodplain formed by extensive vertical accretion. While their planforms may be very similar, their channel geomorphology and floodplain stratigraphy are distinctly different.

Figure 9 presents a revised classification of alluvial single-channel and multiple-channel (anabranching) rivers, modifying that given by Brice (1984). Straight and stable-sinuous rivers are linked together as being laterally inactive; however, straight anabranching rivers can be divided into island-form and ridge-form systems. Individual braid channels commonly migrate (Fahnestock, 1963), as do whole reaches of braided rivers in certain circumstances (Reinfelds and Nanson, 1993). Braided and meandering rivers are therefore linked together as laterally active systems. This classification identifies five types of anabranching river planform: straight island form, straight ridge form, stable-sinuous (all three laterally inactive), meandering and braided (both laterally active). However, because planform is a response to a complex array of interactive

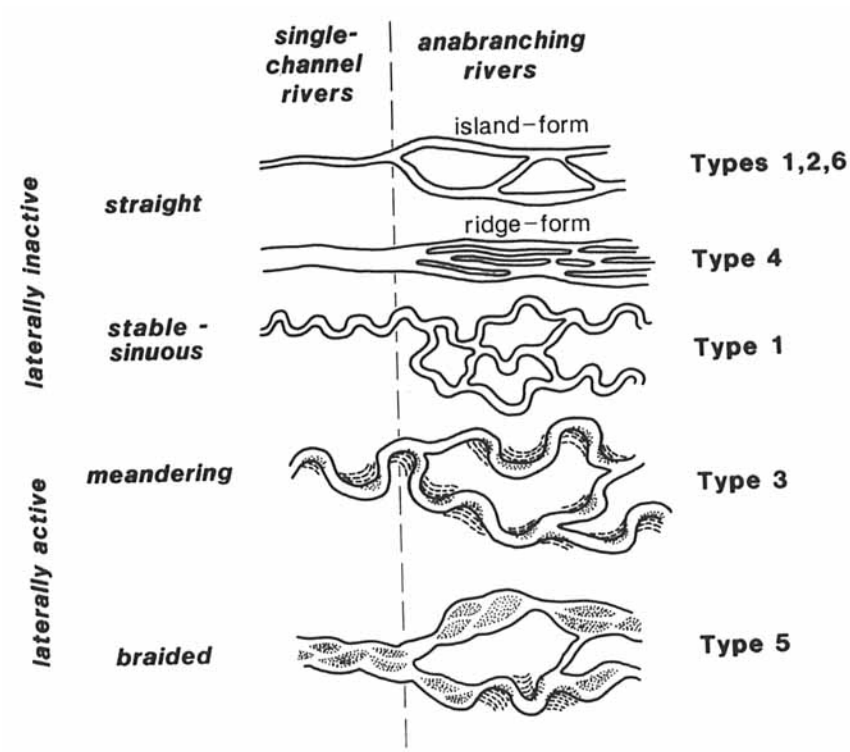

Figure 9. A proposed classification of river patterns including single-channel and anabranching forms. Laterally inactive channels consist of straight and sinuous forms whereas laterally active channels consist of meandering and braided forms

variables, it is not the sole discriminator for river classification. Anabranching types 1, 2 and 6 cannot be separated primarily in terms of planform, although types 3, 4 and 5 can (Figure 9).

When plotted on a bivariate plot of bankfull discharge and channel slope (Figure 1), a method commonly used to discriminate river types (e.g. Leopold and Wolman, 1957; Ferguson, 1981, 1987), none of the anabranching types is distinctly different from its single-channel counterpart. Types 1 and 2 form a group recognized by Knighton and Nanson (1993) as anastomosing; these overlap with Ferguson's (1981) unconfined inactive rivers, albeit plotting at the low-energy end of the range. Types 3 and 4 occupy the mixed-load meandering and sand-load braided river range, and types 5 and 6 are equivalent to transitional braided gravel rivers, where braiding is partially suppressed by bank resistance or low bed-sediment concentrations. In other words, anabranching river systems are not distinguishable in terms of simple slope/discharge plots from meandering, braided and laterally inactive rivers.

CONCLUSION

This study recognizes six types of anabranching rivers that can be classified from low energy, organic or fine-sediment textured systems, to relatively high-energy gravel- or boulder-transporting systems; however, those discussed here are undoubtedly not the full range that will eventually be recognized. They represent a diverse group of rivers but are generally associated with flood-dominated flow regimes, banks that are resistant to erosion, and commonly mechanisms to block or constrict channels and induce channel avulsion. There appears to be a distinction between erosional systems that excavate channels within the floodplain, and accretional systems that build islands within, or floodplains around, existing channels. Anabranching does not preclude meandering or braiding, although it is commonly associated with laterally stable channels. It is a site-specific and process-controlled river pattern that occurs concurrently with other types. It is proposed here that a major advantage that anabranching rivers have over their single-channel counterparts

is that without increasing gradient, they are able to concentrate stream power and shear stress in relatively narrow, deep, unobstructed channels and thereby maintain or increase sediment throughput.

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